TORNADO FORCES
AND THEIR EFFECTS ON BUILDINGS

By

MICHELE G. MELARAGNO

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FOREWORD

DR. MELARAGNO'S paper deals with a subject of great importance to the people of Kansas, and indeed to all those who live in the United States east of the Rocky Mountains. The fury of the tornado and the devastation left by these violent storms is held in fearful awe. Even the early settlers in the Plains States took the precaution to build "cyclone cellars" to protect their lives. Present day warning systems operated by local communities in coordination with the ESSA Weather Bureau have been a tremendous help in reducing the loss of life when these storms strike our ever growing centers of population.

Still, as Dr. Melaragno points out, little concern has been shown in an effort to reduce property damage in the path of these storms. Our awe of the force of these storms has made it easy to place them in the category of irresistible forces. The ability of the reinforced concrete structure to survive the forces of a tornado has cast aside this notion to a certain extent. However, it is still easy to dismiss the "tornado proofing" of the family dwelling as economically infeasible. Dr. Melaragno's review should give encouragement to restudy the methods of construction in light of the more recent observations of the intensity of the tornado. Perhaps municipal and state officials may even want to consider a "building standard" or "code" for "Tornado Alley."

It may not be possible to construct buildings that will survive the center line of the path of intense tornadoes, but it certainly would seem possible to reduce the damage, or control the damage of dwellings at the edge of the path. The Manhattan, Kansas, storm of 1966 and the Garden City, Kansas, storm of 1967 are good examples of types of tornadoes whose damage could be greatly reduced by altering some of our current construction practices. Certainly I think Dr. Melaragno has brought up an interesting problem that is worthy of further study.

L. Dean Bark
Professor of Climatology

PREFACE

THE LACK of information available to designing architects and engineers about the action of tornado forces on buildings has convinced the writer to investigate this subject. The large part of the literature available was found in the field of meteorology and very little in engineering or architecture. An absence of communications between these disciplines was evident.

The purpose of this work is to relate the findings in meteorology to practical applications in architecture. It is hoped that the material presented herein will encourage the practicing designer to consider the feasibility of tornado resistant structures with more optimism.

The author wishes to acknowledge the valuable assistance of Dr. L. Dean Bark for his guidance in meteorological subjects and for his comments on the manuscript. Special thanks to Prof. Keith H. Christensen for his kind and helpful collaboration in this work and to Dr. Philip G. Kirmser for his illuminating remarks on engineering aspects.

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CONTENTS

Tornado Forces

INTRODUCTION

Among the many natural phenomena over which man has no control tornadoes are the most violent. Relatively short in duration and limited in size, they move on the ground, leaving a path of almost total destruction. They occur every year in the plains of the Middle West in the United States and in other parts of the world, but they also occur, with less frequency, in other areas. Many statistical data have been systematically collected on tornadoes concerning occurrence, location, duration, translational speed, dimensions of the path, damage, and loss of human lives. Every year we can be sure that tornadoes will cause millions of dollars of damage and will claim several lives, as they have in the past.[1]

Many scientists in meteorology and other related disciplines are engaged in trying to discover the characteristics of this natural phenomenon. It is hoped that once the mechanics of the storm is known something can be done to overcome it. We can divide the general problem into two fundamental aspects: One is to establish the source of the tremendous energy involved and deduct laws governing the origin of the storm and its actions during its existence and gradual extinction. From this approach possibly a system for neutralizing and destroying such a storm can be found.[2] The other aspect of the problem is to discover the mechanics of tornadoes in order to determine the character and magnitude of the destructive forces involved, and then to establish criteria for protecting structures from devastation by such forces.

The purpose of the present study is closely related to the second approach. Data will be presented that will help the structural engineer to establish his own basic assumptions in his attempt to design a tornado-resistant structure. The data available up to the present are few, and the degree of dependability varies according to the method used in estimating the values or in making the readings; but they do furnish the only usable key at present. While scientists have made several attempts toward solving problems posed by tornadoes, engineers

1. A paper by H. C. S. Thom entitled "Tornado Probabilities" (36) furnishes statistical illustration of tornado occurrence in the United States.

2. There are at present several theories furnishing explanations and hypotheses on this subject. Vernon J. Rossow, for instance, proposes the possibility of an electrostatic vortex as the source of energy for tornadoes, and consequently he proposes destroying them by shorting out the electric field (32). The presentation of other theories is beyond the scope of this study.

have done little about them. Very few structures have been designed with the intent of resisting the violence of these storms. For example a few houses located on Harrison Street in Kansas City were built in 1913 with the intention of being tornado resistant as reported by S. D. Flora (17). He describes these houses as built by Colonel W. H. Nelson with construction criteria derived from observation of damage caused by the tornado which occurred at Omaha, Nebraska, March 23, 1913. General design criteria do not exist and in some instances the few facts that have been established have been purposely neglected because of a lack of interest. In this respect we can point out a report discussed later in this study in which the Task Committee on Wind Forces of the American Society of Civil Engineers intentionally neglects to consider specifications for tornado-resistant buildings on the grounds that there is no demand for them. This fatalistic attitude of accepting the yearly tolls in damages and deaths should be discouraged. Earthquake design is, for instance, a practice accepted throughout the world, governed by codes and enforced by laws. The author strongly suggests, therefore, that tornado forces should be considered and prepared for, as are seismic forces.

Several encouraging points on the feasibility of tornado-proof building are illustrated in this study, including the possibility of reducing pressure differential by venting. Also very important is the excellent performance of reinforced concrete buildings and steel structures which have been in the path of tornadoes, yet have not suffered significant damage.

With the data now available from other disciplines, even if absolute answers are not possible, the more pragmatic structural engineer can be guided in his attempt to solve some of the problems of tornado-resistant design.

MEASUREMENTS

A scientific investigation of tornadoes depends largely on the measurement of the physical forces involved in these storms. This study is concerned in particular with the destructive forces which cause the damages left in the wake of a tornado, such forces as wind pressure and the pressure on the exterior walls of structures that results from the sudden change in atmospheric pressure. The measurements that are discussed herein are, therefore, the ones that define these forces: wind velocity, barometric pressure, and pressure gradient.

Measurements can be divided into two categories: direct measurements and indirect measurements. Under direct measurements we include data derived by direct readings on calibrated instruments. There are several difficulties in setting up the proper instrumentation for direct measurements. The instruments must be designed and constructed to operate properly under the severe conditions, and they must be located in a tornado path. The few figures available concern barometric pressure recorded by chance on the few occasions when a tornado happened to pass over or near a barometer.

The measurements in the category of indirect measurements are derived from other available data when the mathematical relationships between them and the desired measurements are known. Sometimes the mathematical relationship is based on an assumption made subjectively, and this of course reduces the reliability of the results. In other instances the results can be considered as direct measurements because of the direct connection between the data available and the measurements desired.

Most of the values of tornado forces have been computed indirectly by one of the following means:

1. Structural analysis of damages
2. Analysis of ground marks
3. Examination of motion pictures of tornado funnels
4. Examination of splinters that have penetrated other objects
5. Analysis of funnel shape

The derivation of wind velocity from analysis of movies seems to be a very dependable method, giving results that could probably be classified as direct measurement because of the precise calculation possible. Other indirect measurements must be evaluated according to the reliability of the method used.

Translational Velocity

It is an established fact that the major flow of the air in motion at ground level during a tornado is basically circular and translational at the same time. Cycloidal marks observed on many occasions support this assumption. The velocity of the wind is, therefore, the resultant of the vectors representing rotational velocity and translational speed. From this, it is obvious how important it is to know the translational velocity if we want to determine the maximum velocity.

From the many data collected on tornadoes occurring in the United States during past years we can say that the translational speed is a well-known element. This measurement is not too difficult to make, and it is obviously a basic datum necessary to establish the total maximum wind velocity. In his book on tornadoes S. D. Flora gives considerable information on translational speeds (17). He reports the conclusions of a study made by J. R. Martin on the paths of one thousand tornadoes selected at random, and the average speed computed was 45 mph. The speeds, however, vary considerably from storm to storm and even in different parts of the path of the same storm. Sometimes tornadoes remain stationary for a few minutes and then continue on their path.

The minimum velocity recorded was 5 mph for the storm of May 24, 1930, in Pratt, Kansas. The maximum velocity known was 65 mph, which occurred in Kansas from Grenola to Uniontown on May 25, 1917. Flora mentions also the tornado of March 15, 1938, in Batesville, Illinois, which moved at a speed between 60 and 65 mph, and the tri-state tornado of March 18, 1925, which moved at a speed higher than 59 mph in Indiana.

In a Weather Bureau publication (38) the highest tornado forward speed known is indicated to be 68 mph, and this report also confirms the possibility of a tornado becoming stationary. This report concludes that 40 mph is close to the average translational speed.

Morris Tepper, in an article on tornadoes (35) published in **Scientific American,** states that the average speed varies between 25 and 40 mph; the average between these two figures is 32.5 mph.

C. C. Chang, in a paper published by Catholic University (12), states that the linear velocity at which the mother cloud moves and drops the tornado vortex (in other words, the translational speed) is 10 to 50 mph.

The author assumes that probably the speed of 45 mph computed as an average by J. R. Martin is the most reliable. We know, for instance, how he computed it, and the method is very realistic. Certainly the average of one thousand values is a very dependable datum. It is useful to note that knowing the value of the translational speed is vital not just for computing the maximum velocity of the wind but also for computing the pressure gradient, which is the other major cause of tornado destruction.

Estimates of Maximum Wind Velocity

Several statements about the estimated maximum wind velocity occurring in tornadoes have been made by different authors. These statements are not substantiated directly by any measurement but are spontaneous manifestations of ideas and opinions of experts. They must be mentioned in order to give a representative illustration of what is known today about tornadoes.

In 1961 the Task Committee on Wind Forces of the American Society of Civil Engineers expressed its conclusions about tornado forces as follows (3, pp. 1129-30): The peripheral wind velocities have been estimated to be in excess of 300 mph, on the basis of damage done; and the dynamic pressure due to the velocity is 230 psf, which corresponds to an average design pressure of 260 psf.

Flora (17) reports several indicative figures on wind velocities. He mentions on page 13 of his book an estimated maximum rotary wind velocity of 454 mph for the Texas Panhandle tornado of April 6, 1947.

He also mentions that from the observation of damage of many tornadoes the wind velocities derived ranged between 450 and 500 mph. However, Flora admits that much evidence indicates that in some parts of the vortex the velocity was in the order of magnitude of the speed of sound, a conclusion that is in agreement with a theory proposed by Abdul J. Abdullah (1) on supersonic wind speed in the "area limited by the 'limiting circle' and the 'critical circle'."

Chang (12) describes a tornado as a long vortex core with maximum circumferential velocity ranging from 100 to 400 mph.

Morris Tepper (35) reports that the whirling speeds in tornadoes have been estimated at up to 500 mph.

A report of October 7, 1966 (41), by the Department of Housing and Urban Development, presents several recommendations for storm-proofing houses against hurricanes and tornadoes. The report repeats a statement of Mr. F. M. Crompton, engineer in the FHA's Office of Technical Standards, who headed a group of technicians in the investigation of storm damage in Florida and Mississippi: "We know now that the forces of a tornado are not irresistible. We once thought that their velocity was 600-700 miles per hour, but actually it ranges from 100-300 miles per hour and probably approximates 200-250."

Edwin Kessler, the director of the National Severe Storms Laboratory in Norman, Oklahoma, expressed his opinion on tornado velocities in a letter of February 21, 1967, to P. A. Morris of the U. S. Atomic Energy Commission (27). Kessler stated that his personal belief, which he added is "little better than a guess," is that the damages observed in tornadoes could have been produced by wind speeds of 300 knots (150 m/sec, or 335 mph).

A pamphlet from the U. S. Weather Bureau revised in April, 1964 (39), presents a concise list of information on tornadoes, and it states that estimated wind velocity within the tornado is more than 300 mph.

Walter H. Hoecker of the Atmospheric Trajectory Branch of the Environmental Science Services Administration, in a letter of May 8, 1967, to the present author (23) points out that indirectly measured wind speeds approach 300 mph.

In a paper presented at the Fifth Conference on Severe Local Storms in St. Louis, Missouri, October, 1967 (2), several criteria for nuclear power plant design in regard to tornado damage are presented. On page 375, A. E. Swanson, R. E. Stippich, and F. C. Bates report that wind velocities estimated from structural damages have ranged below 250 mph. They also said, "A few estimates have been made of speeds-not-exceeded for structures that have withstood the full force of tornadoes. These range from about 200 to 500 mph. It appears that a maximum wind speed of 300 mph is conservative for the 'average' tornado, and that a speed of 500 mph has a probability in any given storm that is at or below the level of 2 percent."

T. Fujita, D. L. Bradbury, and P. G. Black, authors of a paper entitled **Estimation of Tornado Wind Speed from Characteristic Ground Marks** (20), mention several investigations made by different researchers on structural damages caused by tornadoes, and the proposed minimum wind velocities estimated. In conclusion they wrote, "It seems reasonable to assume that minimum speeds ranging between 55 and 217 mph are required to result in typical damage left behind Midwestern tornadoes."

Maximum Wind Velocity Estimated from Structural Damage. In the Worcester, Massachusetts, tornado of June 9, 1953, three transmission towers were destroyed. C. A. Booker of the New England Power Service Company published an article in **Electrical World,** August 17, 1963 (9), in which he reported several facts concerning the three towers. These towers were previ-

ously tested to failure in the factory and their strength was specifically known. This was of great importance because most conclusions based on structural analysis are affected by the validity of the assumptions made; in this case the test to failure is unequivocally certain. These towers were located on the right of way of the N. E. P. S. C. passing through Shrewsbury at about one mile east of the northern end of Lake Quinsigamond and the Worcester city limits.

The towers destroyed in the tornado were identified as numbers 113, 115, and 116. The direction of the power line supported by the towers was almost 90° from the translational direction of the tornado. Tower 113 was to the left of the path center line. Towers 115 and 116 were to the right. Tower 114, which resisted the tornado winds, was almost in the center.

Considering a counterclockwise circular motion we can say that the three towers were exposed to transverse winds while tower 114 was subjected to frontal winds. According to the sketch illustrating the article by Booker, towers 116 and 115 fell forward and tower 113 fell backward, according to the counterclockwise direction of the rotating winds.

The minimum wind velocities which would have caused the collapse of the towers were 148 mph for tower 113 and 170 mph for tower 116. Engineering calculations show that the velocity near tower 114 was about 343 mph. If the two velocities of 148 and 170 mph were considered to be average velocities existing at the locations of towers 113 and 116, a much higher velocity would have occurred where the peak was expected to be, a peak velocity about twice the average values.

From a research paper compiled at the A and M College of Texas by Stuart G. Bigler (8), we learn of an estimated wind speed determined by structural damage evaluation in connection with four small storms occurring at Avim, Port Bolivar, and Texas City. The tornadoes occurred on March 17, 1957. The analysis of the damage suffered by a water storage tank in Texas City provided the necessary information for the computation of a minimum wind speed required to produce the damage observed. The report shows the computations used by E. P. Segner, Jr., Assistant Professor of Civil Engineering at Texas A and M, and a registered professional engineer. All the data were given to him by the Department of Oceanography and Meteorology at Texas A and M.

The tank in question was 13.58 feet high and had a diameter

of 6.05 feet. In the computations the tank is considered to have been completely full of water. The engineer computed the minimum wind forces required to overturn the tank and to shear the tank off a wooden base. His findings were that the minimum wind forces required to produce those effects were 303 mph for overturning and 285 mph for slippage. Considering that at 285 mph the slippage would occur first, this is the value assumed for the wind speed.

A substantial number of important data on wind velocities can be found in another study made by E. P. Segner, Jr. (33). These data are the results of computations of the minimum wind speed required to produce the damage to various structures during the Dallas tornado of April 2, 1957.

The analysis was conducted for each structure, considering several reasonable modes of failure. The author explains that the results are influenced by so many factors that the results obtained in the study have different degrees of dependability. One point which unfortunately can produce some doubts about the validity of the results is the impossibility of determining whether the damage was due to wind forces only or to flying objects as well.

The results of the study are as follows:

a. Two 8-inch concrete block walls in a service station were blown outward. The two walls were 12 feet high and were oriented perpendicularly to each other. The minimum wind speed calculated was 91.6 mph for one wall and 92.2 mph for the other wall.

b. A small empty storage tank 4 feet in diameter and 5.29 feet high was overturned. The steel tank was 1/8 inch thick, having a weight of 472 pounds empty, and it was supported on four legs braced horizontally. The supporting structure consisted of 1-1/2 x 1-1/2 x 3/16 inch steel angles. The tank was seen by eyewitnesses rolling for about 100 feet after overturning. The author estimates that a minimum wind speed between 55 and 65 mph, with the possibility of much higher values, considering the rolling action after the overturning, was necessary.

c. A flat roof covering a two-story structure was lifted. The roof deck was estimated to weigh 13 pounds/square foot, and was nailed to the supporting 2 x 10 joists. Neither the joists nor the ceiling attached below were damaged, but the deck was blown off. The author assumes that only 50 percent of the common nails anchoring the deck to the joist were effective

and concludes that the uplift was caused by a wind speed of 179 mph.

d. Railroad freight cars were overturned. The author considered eight cars that were overturned and computed the required wind velocity for each car as follows: 128, 144, 144, 217, 83, 144, 105, 143 mph. The conditions for each car were different because of several factors involved such as weight, amount of load, mode of overturning, position of doors (open or closed).

e. A 45-foot elevated signboard collapsed. This structure was built with 13 poles 45 feet high with an approximate diameter of 15 inches. The yellow pine poles were spaced approximately 8 feet on center and were braced together with bracers starting from a point 28 feet from the ground and extending to the top. The signboard supported by the poles was 56 feet long and 17 feet high. The minimum velocity of the wind was calculated to be 302 mph. Among the several modes of failure, the most critical that the author assumed to have been possible consists in the failure of the billboard first and then the collapse of each pile individually under the action of the wind acting on the pile surface. The velocity computed in this case is the highest calculated by the author in his analysis. Noticing the contrast of this value to the other wind velocities the author suggests the possibility that instead of direct wind action the impact from flying objects might have caused the structure failure.

f. Perimeter walls of a rectangular building 200 feet by 160 feet in dimensions collapsed. The exterior walls were 12 inches thick, consisting of 8-inch lightweight concrete block and 4-inch brick interlaced. The wall clearance height was 18 feet, 5 inches. Of the four exterior walls, two collapsed outward, one collapsed inward, and only one resisted the tornado. For the two walls falling inward the minimum wind speed was calculated to be 107 mph, while for the one falling outward the velocity was 109 mph.

g. An empty truckbed overturned. The author assumed that a combination of vertical uplift and horizontal wind action overturned the truckbed and the hydraulic hoist connected to it. He estimated the effects of the shape factor, and therefore he considers the result to be approximate.

h. A flagpole 42 feet high, consisting of three steel pipes of different diameters, was bent. Starting from the base the first

section was 3-1/2 inches OD with a height of 15.5 feet from the ground. The second section, 17.7 feet long, was 3 inches OD, and the third section, 8.8 feet long, was 2-1/2 inches OD. The pole extended 6 feet into the ground and it was embedded in concrete. The pole remained straight for its entire length, but it yielded at the connection with the concrete as shown by the permanent deformation confined to that point. The angle of deviation from the vertical was 10-30 feet. The author considered a minimum yield point of 35,000 psi and estimated the minimum wind speed to produce the yielding at 115 mph, assuming an elastic action, or 133 mph for plastic behavior. The author adds that these values are quite accurate and very reliable.

i. A roof section was removed from a warehouse. The portion of the roof considered in the analysis was 25 feet x 21 feet and consisted of 3-inch, longleaf pine sheathing with 4-ply tar and gravel roofings. The author could not say whether the lifting was due to the typical pressure drop or to suction produced by wind action. The wind velocity estimated was 189 mph; however, the author advised that the accuracy of the result should be assumed to be about 25 percent because of the approximate assumptions about the joint failure.

Maximum Wind Velocity Estimated from Ground Marks. In a study of the Nebraska North Platte Valley tornado of June 27, 1955, Edgar L. Van Tassel arrives at interesting conclusions and derives a wind velocity of 484 mph in the funnel (42).

On aerial photographs taken about 40 hours after the occurrence of the tornado, ground marks are clearly visible on some cultivated fields. The marks are actually ridges or dikes with heights varying from 1/4 inch to 1/2 inch, arranged in waves. They are systematic and elliptical in shape, and the dimensions were calculated by scaling the photographs. The major axis was calculated to be 230 feet and the minor axis 152 feet. The translational speed determined by radar observations was estimated at 12 mph; the average distance between rings at the center of the leading edges was determined to be 15 feet, 4 inches. The basic assumption was that the marks were produced by some object carried by the tornado within the funnel.

The wind speed was determined by the use of the equation $V = eNS$, where V = wind speed, e = the approximate perimeter of the ellipse, N = number of rings per unit length used

in the velocity V, S = translational speed of the tornado, a = 1/2 of the major axis, b = 1/2 of the minor axis:

$$e = 2\pi \sqrt{\frac{(a^2 + b^2)}{2}}$$

$$= 2\pi \sqrt{\frac{[(115)^2 + (76)^2]}{2}} = 2\pi \sqrt{9500}$$

$$= 2\pi \text{ x } 97.5 = \frac{613 \text{ feet } \pm}{5280} = 0.116 \text{ mile}$$

Number of orbits in one mile: $N = \frac{5280}{15.3} = 345$

Assumed: $S = 12$ mph

$V = 0.116 \times 345 \times 12 = 484$ mph

Several wind velocities have been estimated by an analysis made of ground marks visible along the paths of tornadoes after the occurrence of the storms. These marks are usually of cycloidal shape, indicating two component paths—one rotational and the other rectilinear—representing the rotational and translational motion of a point moving with the tornado.

Interpretations of the mechanics of the formation of these marks vary among the researchers investigating the phenomenon. Van Tassel assumes for instance that the marks are produced by an object picked up by the tornado winds and moving according to the direction of the wind. Three authors of a paper presented at the Fifth Conference on Severe Local Storms at St. Louis in 1967 have a different opinion (20). Fujita, Bradbury, and Black, at the University of Chicago, assume that among several different types of marks left on the ground by tornado action one, of cycloidal shape, is produced by a suction action. In their paper they explain that around the tornado center there are several spots in which this suction action is concentrated; these spots are not larger than 50 feet in diameter and rotate around the tornado center. The suction power of these points is one order of magnitude smaller than that of a household vacuum cleaner.

In analyzing the cycloidal suction marks left by the tornado of April 21, 1967, which extended from southwest of Belvidere to north of Woodstock, Illinois, these researchers conclude that the rotational speeds on two occasions were 160 mph and 150 mph. The translational speed of that tornado was measured to be 50 mph. The resultant velocities, found by adding vec-

torially the rotational and translational speeds, were, then, 210 and 200 mph, respectively.

The same authors report, on page 43, that using the same approach they computed several velocity values for the suction spots observed after the Fargo tornadoes of June 20, 1967, and the resultants of rotational and translational velocities were 172, 176, 173, 180, 180, 173, and 166 mph. In this case the translational speed was 62.5 mph. These values are very close to velocity values calculated by Fujita when he analyzed the motion pictures of the Fargo tornadoes. This is of course very encouraging, because the two methods of analysis are completely different, while the results seem to be nearly equal.

Wind Velocity Derived from Scaling Motion Pictures. A large number of tornado wind velocity values have been derived by Walter H. Hoecker, Jr., for the Dallas tornado of April 2, 1957, as reported in an article in the **Monthly Weather Review,** May, 1960 (25). High-quality tornado movies were available for the study of the Dallas tornado, including some scenes taken with a ten-times magnifying telephoto lens. In the funnel, fragments of clouds and debris were clearly visible in their circular motion, and their location at different time intervals could be identified quite accurately because the time periods between pictures were known.

A distribution of wind velocities in mph at several points located at different radial distances from the axis of the tornado funnel, and at different elevations from the ground, is represented in Figure 2 of Hoecker's paper. The wind velocities were determined only at those points where, by chance, tracer particles were located; it is probable that higher wind velocities could have existed at points different from the ones analyzed. And it must be noted that the author assumes that the moving tracer elements, cloud fragments, debris, and dust particles were moving at the same speed as the air in which they were imbedded.

The largest velocity value derived was 170 mph, which is a tangential component of the velocity. The point where this velocity occurred was located at an elevation of 225 feet from the ground and at 130 feet radial distance from the center of the funnel.

Tangential wind velocities have been derived by Tetsuya Fujita for the Fargo tornadoes of June 20, 1957, from a study made of motion pictures showing the tornado in action (21). Fujita explains that he analyzed seven cloud pendants appear-

ing at the base of a sheared-off funnel just above the ground. These cloud pendants were located at a radial distance from the funnel center of 296 feet, 196 feet, 98 feet, 196 feet, 360 feet, 328 feet, and 296 feet. The velocities were, respectively, 112, 112, 93, 100, 111, 100, and 102 mph. Fujita mentions the fact that these values are very close to velocity values computed by analyzing cycloidal suction marks.

Maximum Wind Velocity Estimated from the Shape of the Funnel. A. M. Glaser, in a paper entitled "An Observational Deduction of the Structure of a Tornado Vortex," reported in 1959 the maximum tangential wind speed computed for the tornado of March 21, 1956, in Texas. The method used was based on the evaluation of the shape of the tornado funnel. Fujita (20), on page 2, reports Glaser's calculation of maximum tangential wind speed as 230 mph. This tangential wind speed was computed for an elevation of 820 meters above the ground and at a radial distance of 61 meters from the center.

Table 1.—Wind Velocity Estimates

Maximum Speeds		
Task Comm. on Wind Forces (3)		over 300 mph
Flora (17)		500 mph
Chang (12)		400 mph
Tepper (35)		500 mph
Crompton (41)		300 mph
Kessler (27)		335 mph
Weather Bureau (39)		300 mph and over
Hoecker (23)		300 mph
Swanson, Stippich, Bates (2)		500 mph
Fujita (20)		217 mph
Average Maximum Speeds		
Flora (17)		450 to 500 mph
Chang (12)		100 to 400 mph
Crompton (41)		200 to 250 mph
Swanson, Stippich, Bates (2)		200 to 500 mph, 300 mph most probable
Maximum Speeds Estimated from Structural Damage (These values represent speeds required to cause damage observed. Actual maximum speeds may, of course, be higher)		
Booker (9)	Transmission tower	148 mph
Booker (9)	Transmission tower	170 mph
Booker (9)	Transmission tower	343 mph
Bigler (8)	Water tank	285 mph
Segner (33)	Concrete block wall	91.6 mph
Segner (33)	Concrete block wall	92.2 mph
Segner (33)	Storage tank	65 mph
Segner (33)	Roof	179 mph
Segner (33)	Railroad freight car	128 mph
Segner (33)	Railroad freight car	144 mph
Segner (33)	Railroad freight car	144 mph

(Continued next page)

Table 1.—Wind Velocity Estimates (Continued)

Maximum Speeds Estimated from Structural Damage (These values represent speeds required to cause damage observed. Actual maximum speeds may, of course, be higher)		
Segner (33)	Railroad freight car	217 mph
Segner (33)	Railroad freight car	83 mph
Segner (33)	Railroad freight car	144 mph
Segner (33)	Railroad freight car	105 mph
Segner (33)	Railroad freight car	143 mph
Segner (33)	Signboard	302 mph (doubtful)
Segner (33)	Brick and block wall	107 mph
Segner (33)	Brick and block wall	109 mph
Segner (33)	Truckbed	133 mph
Segner (33)	Roof	189 mph
Maximum Speeds Estimated from Cycloidal Ground Marks		
Van Tassel (42)		484 mph
Fujita, Bradbury, Black (20) 21 Apr. 67		210 mph
Fujita, Bradbury, Black (20) 21 Apr. 67		200 mph
Fujita, Bradbury, Black (20) 20 June 57		172 mph
Fujita		176 mph
Fujita		173 mph
Fujita		180 mph
Fujita		180 mph
Fujita		173 mph
Fujita		166 mph
Maximum Tangential Speeds Estimated from Scaling Motion Pictures		
Hoecker (25)		170 mph
Fujita (21)		112 mph
Fujita (21)		112 mph
Fujita (21)		93 mph
Fujita (21)		100 mph
Fujita (21)		111 mph
Fujita (21)		100 mph
Fujita (21)		102 mph
Maximum Speeds Estimated from Funnel Shape		
Glaser (20)		230 mph

Estimates of Maximum Pressure Differential

Several authors have expressed opinions on the variation of pressure that can be found in the tornado path. Some of these estimates of maximum expected pressure differential are mentioned here for the purpose of illustrating the subject more completely.

Finley (31) considers the possibility that in the center of a tornado vortex the condition is a near-vacuum because of the centrifugal force of the tornado cloud (about 2000 psf).

Teesdale (31) gives an estimated maximum value of pressure drop up to half of an atmosphere, about 1000 psf.

C. F. Brooks (31) assumes the pressure in the funnel to vary between 4/5 of an atmosphere and 1/2 of an atmosphere (from 1600 psf to 1000 psf).

Ferrell (31) assumes the pressure in the funnel to be 3/4

of an atmosphere, which means that 1/4 of an atmosphere is the reduction [2000 psf — $(3/4 \times 2000) = 500$ psf].

Logie (31) claims that the reduction of pressure exceeds 50 mb (104 psf), and he adds that many authorities assume that 500 mb (1040 psf) could be the maximum value.

Humphrey (31) believes the reduction of pressure to be about 1/10 of an atmosphere (about 200 psf).

E. M. Brooks (31) states that a probable value could be greater than 200 mb (418 psf).

Abdul Jabbar Abdullah (1) arrives at a minimum pressure of 520 mb at the limiting circle of the tornado, starting from a pressure of 1000 mb at infinity. The pressure drop is therefore 470 mb at the limiting circle, and the author assumes that this value could be also considered valid for the center of the funnel. A pressure drop of 470 mb is equal to a pressure of 981 psf.

Edwin Kessler (27) suggests the figure of 300 knots for maximum wind speed, or an equivalent pressure drop of about 200 mb, according to Bernoulli's equation. $(200 \times 2.088 = 418$ psf)

Unofficial Pressure Differential Measurements. One of the largest drops of atmospheric pressure recorded during a tornado is an unofficial measurement of questionable reliability. Yet several authors interested in this subject have mentioned this exceptionally high pressure differential reading, so that it has become almost accepted (15, 31, 38). In reporting this value there are some slight differences among authors. An article on the tornado which passed through St. Louis in the afternoon of May 27, 1896, was published in the **Monthly Weather Review** in 1896 (18). In a footnote to the article, the author explains that he was given an aneroid barometer with a metrical scale to be reset. He learned that the barometer belonged to the widow of a Mr. Klemm, former Park Commissioner of the city. It had been in Mrs. Klemm's house, and at the time the tornado struck her son read the barometer at 680 mm (26.78 inches). Frankenfield, the author, compared this reading with the official readings by the U. S. Weather Bureau office in St. Louis and corrected the value of 26.78 inches to 27.30 inches to take into consideration the difference in elevation between the Klemm house and the Weather Bureau office. The difference he reported is 2.05 inches.

A November, 1965, publication by the Weather Bureau, "Tornado Facts" (38), reports the same differential pressure

reading to be 2.42 inches. A. W. Reynolds (31) discusses the same instance, indicating that the variation between the two readings was between 2 and 2-1/2 inches. Flora, too, mentions the same series of events in his book on tornadoes (17).

The **Monthly Weather Review** published another article, in September, 1896, giving additional information on the subject. A civil engineer in St. Louis, Mr. Julius Baier (6), made a complete investigation of the circumstances surrounding the reading of the pressure by Mr. Klemm's son. He also checked the accuracy of the instrument at Washington University. Baier's conclusions are explained in a report addressed to Frankenfield, which is included in the article. The original value of 27.30 inches, representing the corrected reading on the barometer during the tornado as computed by Frankenfield, should be instead 26.94. This additional 0.36 brings the pressure differential from 2.05 to 2.41 inches (170.47 psf).

In the report on the tornado of August 20, 1904, in Minneapolis, Minnesota, in the **Monthly Weather Review** of that year (29), an unofficial pressure differential reading is mentioned. The reading is exceptionally high and therefore questionable; however, the author of the report seems to be convinced of the dependability of two persons who measured the barometric pressure. The article reports that these two gentlemen observed an aneroid barometer dropping to 23 inches and then rising almost immediately to the original position, which is not mentioned. Assuming that the initial reading was the same as the one observed by the local forecaster (28.67) the drop was 5.67 inches (401 psf). As an additional fact to validate the accuracy of the instrument, the article adds that the aneroid barometer had been checked at the weather station and compared with other instruments not very long before, and it had been found to be correct.

Official Pressure Measurements. The first recorded official measurement of pressure variation in the eye of a tornado is probably the one reported in the **Monthly Weather Review** in reference to the tornado that struck Little Rock, Arkansas, the evening of October 2, 1894 (37). The center of the tornado seemed to have passed right over the telegraph office where the local Weather Bureau office was located. George S. Harkness, who was the observer at the office, made a report of the events:

The tornado struck a building on the south side of the office,

throwing the second story over the office-building roof. Then the windows in the office were blown in. The wires connecting the instruments on the roof with the recording apparatus were broken, and many instruments were damaged. This happened at 8:28 p.m., and it appeared to Mr. Harkness that the tornado passed over the office in about one minute. During this minute the self-recording Richard barograph recorded a drop of 0.38 inch in the barometer. The diagram which furnishes the record of the variation of the barometer indicates that after a slight oscillation the pressure dropped in a straight line from 29.31 to 28.93 and returned so quickly that it is difficult to tell the time elapsed during the oscillation.

The horizontal movement of the paper of the barograph was at such a rate that the recorded oscillation could have occurred in one minute or less, and it is not possible to establish the time period exactly; the trace of the pen would have been practically the same whether the time had been one minute or one second. Even if the pressure gradient cannot be defined, this datum has great significance because of its dependability.

A reliable pressure reading was taken during the tornado that passed over Dyersburg, Tennessee, on March 21-22, 1952 (11). A weather station operated by the Civil Aeronautic Authority is located at the local airport, and the barograph was assumedly in the station. The tornado path at that point was 258 yards wide and the barograph was in the path, located exactly 41 yards from the center line. The reading indicated a pressure drop of 0.65 inch (45.98 psf). J. A. Carr, who reported this information in an article in the **Monthly Weather Review,** adds a comment on this measurement indicating that the real drop may have been higher than the value indicated on the barogram trace because of a probable lag in response of the instrument.

On August 20, 1904, a severe storm which seems to have been a tornado struck Minneapolis, Minnesota. A report on that storm was published in the **Monthly Weather Review** by T. S. Outram, local forecaster (29). The official pressure reading was 28.82 inches, which gradually fell to 28.67 after noon. "Just about the time of the greatest severity of the storm the barograph dropped suddenly to 28.25, returning immediately and rising to 28.80, then dropping back quickly to 28.70." It then fell gradually until the next day. The jump of 0.55 inch is an official reading.

Pressure Values Estimated from Scaling Motion Pictures. Probably the most interesting and valuable data on pressure differential are the results presented by Walter H. Hoecker, Jr., who estimated wind speeds in the Dallas tornado of April 2, 1957, from high-quality movies showing the funnel and the movement of cloud fragments and debris circulating around the tornado. The first study was published in the **Monthly Weather Review** of May, 1960 (25). His Figure 2 is a diagram of the wind velocity in mph at several points located at different elevations above the ground and at different radial distances from the funnel center. Curves connecting points of equal velocity (isotachs) are also shown in the same figure. At this point it should be pointed out that although velocities are indirect measurements they are logical consequences of the direct measurements made. If the measurements from which the velocities are derived are correct, then the velocities too are correct. The interval in time between one frame and the next is definitely known. The distance between two different locations of the same object at two different instants can be accurately scaled from the pictures. We must conclude, therefore, that these measurements are almost direct measurements, not based only on theoretical assumptions.

In a second paper, published in the **Monthly Weather Review** of December, 1961 (24), the author elaborates on the wind velocity values already derived and computes the values of the pressure gradients at the same points at which he had previously determined the wind velocity. To obtain the pressure gradients in millibars per meter Hoecker uses the cyclostrophic wind equation

$$\frac{\rho p}{\rho r} = \frac{\rho v^2}{r},$$

where p = pressure, r = radial distance from tornado center, ρ = density, and v = velocity. In the use of this equation some assumptions are made, and even if they are theoretically justified the resulting values cannot be considered as close to direct measurements as are the velocity values derived above. The author refers to studies made by Long and Glaser for justification in using the cyclostrophic equation.

In Figure 1 of Hoecker's second article, a diagram represents the distribution of the pressure with respect to the distance from the tornado axis and the elevation above the ground. Assuming the translational tornado velocity to be 27 mph as the average value for that particular storm, the author constructed another diagram which is the representation of

the variations of the pressure at ground level. The data that can be derived from this diagram are very useful in the design of a venting system, because any calculation in determining venting sizes must be based on pressure and time factors. The maximum value of the pressure drop computed by Hoecker was 60 mb, which expressed in inches of Hg is 1.8, corresponding to a pressure of ±125 psf.

Table 2.—Pressure Differential Estimates

Estimated Maximum Differentials	
Finley (31)	2000 psf
Teesdale (31)	1000 psf
C. F. Brook (31)	1000-1600 psf
Ferrell (31)	500 psf
Logie (31)	1000 psf
Humphrey (31)	200 psf
E. M. Brook (31)	418 psf
Abdullah (1)	981 psf
Kessler (27)	418 psf
Unofficial Records	
Monthly Weather Review (18)	170.47 psf (2.41″ Hg)
Weather Bureau (38)	
Reynolds (31)	
Flora (17)	
Baier (6)	
Monthly Weather Review (29)	401 psf (5.67″ Hg)
Official Records	
Carr (11)	0.65″ (45.98 psf)
Harkness (37)	0.38″ (26.88 psf)
Outram (29)	0.55″ (38.9 psf)
Pressure Values Estimated from Scaling Motion Pictures	
Hoecker (24)	60 mb (125 psf)

Pressure Gradient

Data on pressure gradient are very limited—unfortunately, this is an essential element in computing venting area necessary to balance the pressure differential between the inside and outside parts of buildings enveloped in a tornado. George W. Reynolds (31) has derived an empirical value for pressure gradient of 1 inch of mercury per 120 feet and suggests that although there is not enough evidence it can be expected that only houses in the center of the vortex ever experience a pressure gradient much in excess of this value.

In order to derive his figure for probable pressure gradient, Reynolds considered that the average tornado damage path is about 1/4 mile wide and the average translational velocity is about 40 mph. With these assumptions he considered that a point at the edge of the limit of destruction located on the axis

of translation of the center of the funnel would be right in the center after a time period of 11 seconds. This procedure assumes that the pressure varies linearly from the undisturbed area to a minimum value at the center of the tornado. Reynolds too realized that probably the pressure gradient would be greatest near the tornado center.

Hoecker computed the pressure gradient from his analytical study of the Dallas tornado of April 2, 1957, after he determined the velocity and the pressure field from motion pictures of the tornado (24). The maximum value of the pressure gradient that Hoecker computed is 26 mb/sec, which occurred for a period of 0.5 second about 4 seconds before the center of the tornado reached the point under consideration. The diagrams illustrating the pressure gradient, Figure 6 and Figure 7 in Hoecker's paper, clarify the results that the author obtained. It is important to mention that these values for the pressure gradient were determined considering the pressure field previously computed and translating it at a speed of 27 mph, which was the established average translational speed of the tornado in question. Obviously the data are therefore as accurate as the dependability of the translational speed, which could have been different from the average value used.

MISSILES PENETRATION

It appears that this aspect of tornado phenomena is now under detailed study. According to a letter to the editor published in **Weatherwise** in December, 1967 (4), Arthur D. Little, Inc., seems to be engaged in a project supported by the National Severe Storm Laboratory of ESSA. The purpose of the project is to determine the wind velocity required to accomplish the penetration of splinters into trees and posts that occurs during tornadoes. The company has built an air gun with a 0.12-inch bore capable of accelerating a rodlike object to sonic velocity. This will enable the researcher to study penetration phenomena under controlled laboratory conditions by reproducing the imbedding of splinters into objects that has been observed in samples found after tornadoes occurred. A systematic analysis based on this practical experimentation will be of great significance, especially considering the large number of examples that could be available.

Many authors have reported the phenomenon observed after the striking of a tornado of objects penetrating into other

objects quite deeply, indicating a very high velocity impact. M. O. Asp (5) refers to this common occurrence, mentioning in general straws and shingles driven into boards and trees, and straw driven into automobile tires between the casing and the wheel.

H. C. Frankenfield (18), writing about the tornado of St. Louis of May 17, 1896, reported that a 2-inch x 8-inch white pine plank was driven into the side of a steel girder, punching a hole in the web and remaining fastened to it. This phenomenon was observed on the approach to the St. Louis bridge over the Mississippi.

Flora (17) reports some freak incidents that can be explained only if the wind speed was in the order of magnitude of the speed of sound. He mentions the penetration of an old rafter into the side of a new house, a situation that he and a Weather Bureau official verified personally. In the light of the circumstances, the speed of the impact must have been tremendous. Flora also mentions other unexplainable events that seem difficult to believe. However, we must remember the work of A. J. Abdullah (1) in which he concludes that supersonic speeds are reached in some points of the funnel.

THE MECHANICS OF TORNADOES

The penetration of some proposed models of the mechanics of tornadoes should be helpful in visualizing the action of the forces present in the storm. The two references that have been selected for this illustration are of different character: one in a very theoretical study of the phenomena occurring in the storm, based upon mathematical derivations from which are developed basic theoretical assumptions; the other is a very practical interpretation of observations made during a tornado which the author witnessed personally.

In April, 1955, the **Monthly Weather Review** published an article by Abdul Jabbar Abdullah (1), in which was presented a dynamic model of a tornado based on several assumptions. Abdullah started from the theory formulated by D. Brunt, who stated that a strong convective vertical current on a rotating disc may be sufficient to initiate a vortex. Abdullah then assumed that the air is a compressible fluid, allowing the possibility of creating kinetic energy by a transformation of internal energy. After a description of a mechanical model for the **formation** of a tornado he then described the model for a

mature tornado. He divided the field of action into three concentric circular areas:

1. The outermost field, which goes from infinity to the "critical circle."

2. The supercritical region, which extends from the "critical circle" to the "limiting circle."

3. The innermost circular field, which is enclosed in the "limiting circle."

The outermost field is an area of flow where the velocity has subsonic values. The particles of air are attracted toward the center of the tornado, where a low pressure exists, and move toward this point. The flow is radial and rotational, and the particles of air describe spiral paths while they approach the center. In this field the law of conservation of angular momentum is applied and the particles have a higher velocity when approaching the center.[3] When the particles reach the critical circle they have reached the local speed of sound, and they have also acquired a vertical component so that they are rising in spiral paths.

The supercritical region is an extension of the outermost field. The particles are rising in spiral paths and are moving at supersonic speed, increasing their speed according to the law of conservation of angular momentum as they approach the center. When the particles reach the limiting circle they are not able to pass through and they escape vertically along the surface of the cylinder enclosing the innermost circular field. The particles of air on the outside of the limiting circle do not have infinite velocity, but they have infinite acceleration.

The innermost circular field is a cylinder whose radius is called the minimum radius (r_m). In this area there is a jet of air moving upward. This air has not passed through the two surrounding areas but is penetrating inside at the ground level where the friction between the ground and the air breaks the continuity of the mechanism.

The values of the minimum radius and the critical radius have been computed by Abdullah on the basis of the following assumptions:

a. the radial velocity at 40 km from the center is assumed to be 1 cm/sec;

3. The law of conservation of angular momentum can be expressed by stating that the moment of the tangential speed about the center of rotation is constant for any radius.

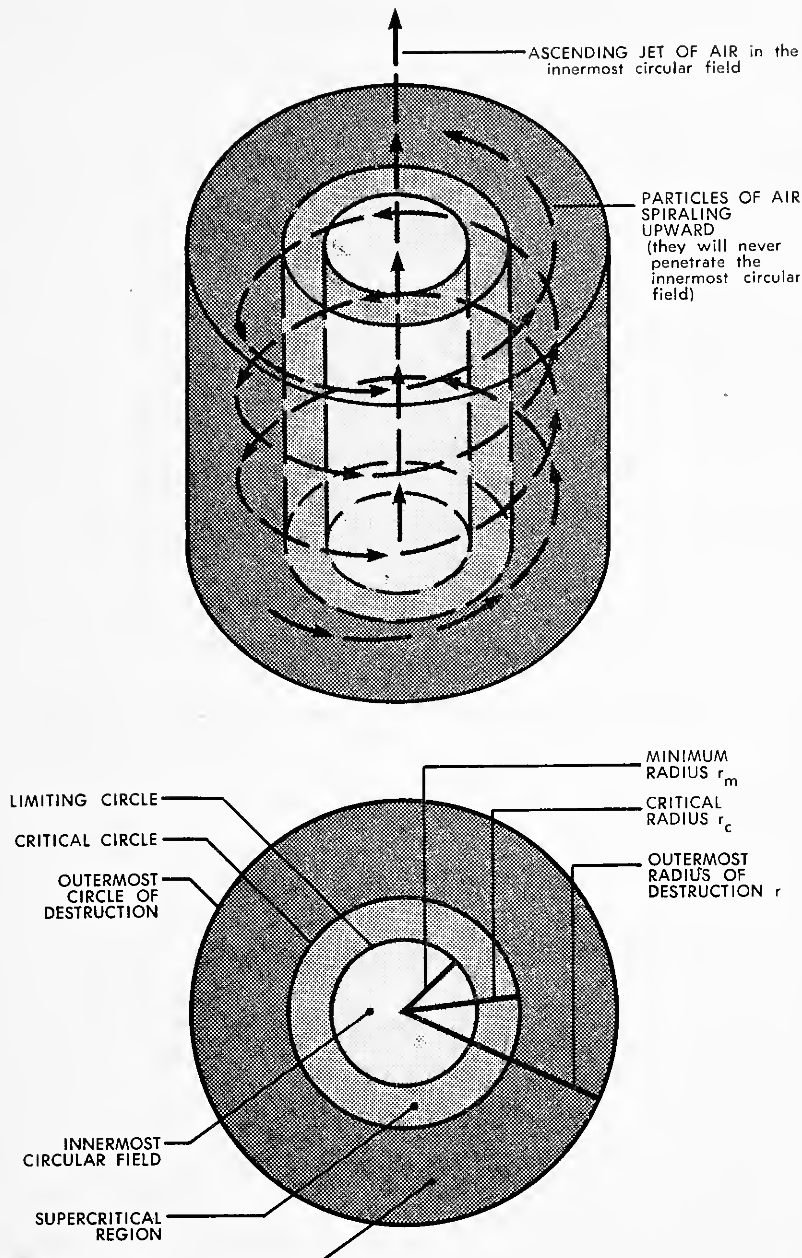

Figure 1. Model of a Tornado, A. J. Abdullah (1).

b. the sonic speed at infinity is assumed to be 3.3×10^4 cm/sec;

c. the undisturbed density is assumed to be 10^{-3} gm/cm^3.

Table 3.—Minimum Radius and Critical Radius (meters)

r_m	r_c	r_c-r_m	r
2.09	2.09	0	21
2.67	2.78	.11	28
2.94	3.22	.28	32
3.33	3.75	.42	38
3.71	4.32	.61	43
4.09	4.96	.87	50
7.1	10.3	3.2	100
9.70	14.0	4.30	140
32.2	60.3	28.1	600
77.5	158	80.5	1580
139	296	157	2960
259	570	311	5700

Abdullah concludes that the area of destruction can be considered to originate where winds of 100 km/hr occur. This speed is about 1/10 of the sonic speed at normal temperature. Since at the critical circle the wind velocity is near sonic speed he infers that the radius of the area of destruction is about 10 times the critical radius.

Frank B. Dinwiddie gives a very clear description of the mechanics of a tornado in a paper entitled "Waterspout-Tornado Structure and Behavior at Nags Head, N. C., August 12, 1952" (15). He explains that a vertical hollow tube with a wall consisting of a mass of air rotating counterclockwise at very high speed touches the ground. At ground level the air moves radially toward the circular base of the hollow tube. As it approaches the circle the air is gradually rotating counterclockwise as is the vertical tube. The air on the right side of the funnel, looking in the direction of the translational movement, has greater speed than the air on the left side. The wall of the tube where the velocity is the highest is almost like a solid barrier so that air cannot penetrate through the wall. At the base, however, the air can enter the tube; the friction between the tube and the ground reduces the velocity of the air in the tube, allowing the air to penetrate the tube. The air which enters the tube rises, forming a vertical jet that produces a lifting suction of objects. The objects that have been picked up rise and rotate inside the tube and then

by centrifugal force break through the walls and fall back to the ground.

DIRECTIONAL ROTATION

The direction of the vortex is usually counterclockwise in the northern hemisphere because of the deflection due to the Coriolis force. Tornadoes, however, have revolved in a clockwise direction in the northern hemisphere on many occasions. Flora (17) mentions on page 27 a study made by J. P. Finley and published in the **American Meteorological Journal** in 1890: Finley reported that in a study made of 500 tornadoes that occurred in the United States, 29 were found to have a clockwise direction of rotation.

EFFECT OF PRESSURE DIFFERENTIAL

It is commonly agreed that the pressure differential produced by the mechanics of tornadoes together with the wind pressure is the major cause of damage when these storms strike.

The variation of pressure is caused by a reduction of pressure within the funnel due probably to the centrifugal force of the rotating mass of air. A building enveloped in the tornado funnel will be surrounded by a pressure which is lower than the pressure that existed before the funnel enveloped it. The air inside the structure which did not escape in time is still at the atmospheric pressure existing before, which is higher than the pressure outside the structure.

The variation of pressure generates, therefore, a pressure load outward on the exterior walls of a building. This load can be considered a uniformly distributed load perpendicular to the exterior surface. When this load is applied to the walls, the structure may yield to it. If all parts of the building have uniform strength the entire structure may collapse; if part of the structure is more critically vulnerable, such as the roof in many wood frames, that part will yield first.

When the air from the inside escapes, equilibrium between the exterior and the interior pressure is established. If the structure is particularly strong the equilibrium may be reached by release of the air from inside through broken windows, without bursting the exterior walls or roof.

When the funnel which has enveloped the building has passed on, the pressure outside will rise to its original point. Now, if air escaped from the building in order to balance the

interior and exterior pressures while the funnel surrounded the building, the situation is reversed, and the building will experience the same pressure load directed inward. This second blow to the structure could be more critical than the first, considering that even if the structure resisted the first action some yielding might have occurred, weakening the structure so that the second force could be fatal.

Several authors in describing the action of this pressure variation refer to it as an explosive force, and the kinds of damage produced by this force validate this description. An important factor in the application of this pressure is the time. The pressure is applied instantaneously or more exactly within the time related to the translational speed of the tornado. We have seen that a known translational speed has been determined for many tornadoes. It is, however, an average velocity. We do not know the exact instantaneous velocity of translation. Sharp changes in the path of the tornadoes are indicated by surveys of damaged areas. These short sharp translational motions could take place at a higher speed than the average translational speed, increasing the value of the pressure gradient.

The pressure gradient, which indicates the rate of pressure increase or decrease with respect to time, denotes that this pressure is not static but rather dynamic, like an explosion. A pressure load which grows from a given value to its maximum intensity in a short time is an impact load, or a dynamic load. To be more specific, we can say that the load is dynamic if the time required for the load to grow from its minimum intensity to its maximum is shorter than the fundamental period of the structure on which the load is applied.

We can also add that the fundamental periods of the single parts of which the structure consists are important; but the most critical fundamental period in our case is the largest, because the loads become dynamic only if the period of the load is smaller than the fundamental period of the structure. Usually the structure as a whole has a larger fundamental period than the single structural components.

A dynamic load is usually equivalent to a static load of greater intensity. The magnification factor is a number larger than one and is a function of the fundamental period of the structure.

When we try to determine the forces produced by the wind on a structure we are solving a dynamic problem. Usually it is easier to convert the dynamic problem into an equivalent static problem; however, we must be sure to interpret the several factors involved in the right way.

The wind is a mass of air in motion which possesses a kinetic energy because of its mass and velocity. Any obstacle which reduces the velocity of this air or changes its original path is converting part of the kinetic energy into potential energy of pressure which the obstacle will absorb or dissipate. This potential energy of pressure on the obstacle (which we consider to be a given structure) is a function of several factors such as wind velocity, mass of air, shape of the obstacle, and angle of incidence of the wind.

The velocity and the mass of the air flowing in a wind are the two factors that are involved directly in the transformation of kinetic energy into energy of pressure as it appears in the Bernoulli theorem which follows:

$$1/2\ \rho\ v_0^2 + 1/2\ \rho\ v^2 + p = \text{constant}$$

p_0 = static pressure of free air in the undisturbed wind.

p = static pressure of air at a given point located on the obstacle.

v_0 = velocity of undisturbed wind

v = velocity of the wind in the same point at a given point on the obstacle.

$1/2\ \rho\ v_0^2 = q_0$, dynamic pressure of the undisturbed wind.

$1/2\ \rho\ v^2 = q$, dynamic pressure of the wind at a given point on the obstacle.

Bernoulli's equation basically states that the total energy of an ideal fluid in motion is always constant.[4] This total energy is the sum of a kinetic energy and a potential energy of pressure. One form of energy can be transformed into the other, but the total is always constant. When a mass of air in motion is disturbed by an obstacle which varies the velocity of the air, reducing it, part of the kinetic energy is transformed into potential energy of pressure.

Bernoulli's equation can be applied at every point of the

4. Bernoulli's equation takes into consideration only ideal fluid, which does not have viscosity and friction. We are considering air as an ideal fluid when we use this equation.

obstacle and we could see that according to the shape of the object the velocity of the air which was originally v_0 becomes v_1 v_2 v_3 etc., at P_1 P_2 P_3. At each point P_1 P_2 P_3 we will have different static pressures p_1 p_2 p_3 produced by the transformation of q_1 q_2 q_3 ($q = 1/2\ \rho\ v^2$) dynamic pressure into static pressures.

Multiplying the pressure by the area on which the pressure acts we have an elementary force, qA.

The resultant of all these elementary forces will be the **net force** applied in the center of gravity of these forces, which we could call the center of pressure. The net force can be subdivided into two components: F_D (**Drag Force** parallel to the wind), and F_L (**Lift Force** normal to the wind).

$$F_D = C_D\ q\ A$$

$$F_L = C_L\ q\ A$$

C_D and C_L are coefficients which are called, respectively, the "drag coefficient" and the "lift coefficient"; both are determined experimentally. These coefficients, which are part of these forces, depend on the shape of the obstacle and the angle of incidence of the wind.

BUILDING DESIGN FOR WIND FORCES

We have seen the general problem concerning the interaction between a solid object and a fluid during the movement of one with respect to the other. It makes no difference whether the body is at rest while the fluid is flowing or the body is in motion while the fluid remains still. The drag force and the lift force, however, although theoretically applicable to any problem, are in practice used in aerodynamic design where the fluid stays still and the body moves. In this case usually the direction of the relative movement is known because the body (a vehicle in most cases) moves in a single direction with respect to a system of coordinates referred to the body. The drag and lift forces are therefore applied at the same point. In the case of a building subjected to wind forces these quantities are not practical, because the wind may have many different directions with respect to the building.

The degree of accuracy in building design is considered less critical than in aerodynamic design, and therefore rather than considering the total drag force we consider a static pressure p uniformly applied over different surface areas of the building.

To establish p we start from the dynamic pressure: q =

$1/2\ \rho\ v^2$, where ρ = density of the air in slugs/cf, v = velocity of the wind in ft/sec, q = pressure in psf.

For practical reasons it is better to use the following formula: $q = 0.00256\ v^2$, where q = psf and v = mph. The coefficient 0.00256 which appears in the formula includes the conversion factor for changing the unit of measure for the velocity from ft/sec to mph. In addition, the same coefficient includes the density of the air assumed to be $\rho_0 = 2.378 \times 10^{-3}$ slugs/cf. This is the value of the density of the air at 15°C and at a pressure of 760 mm Hg in a dry condition. (Note that 15°C = 59°F and 760 mm Hg = 29.92 inches Hg.)

The approximation resulting from assuming a constant value of the air density is quite accurate. As an example, the value of air density for a much higher temperature and a lower atmospheric pressure is indicated below, and it is evident that the variation is negligible for design purposes:

Variation of air density ρ with pressure p and temperature: t°:

using standard conditions the equation is

$$\frac{\rho}{\rho_0} = \frac{p t_0^\circ}{p_0 t^\circ}$$

$$\frac{\rho}{\rho_0} = 3.3789 \frac{p(\text{mm Hg})}{(t^\circ\text{C} + 273^\circ\text{C})}$$

$$\frac{\rho}{\rho_0} = 9.624 \frac{p\ (\text{in Hg})}{(t^\circ\text{C} + 273^\circ\text{C})}$$

$$\frac{\rho}{\rho_0} = 17.32 \frac{p\ (\text{in Hg})}{(t^\circ\text{F} + 459.4^\circ)}$$

Variation of air density with altitude:

$$\frac{\rho}{\rho_0} = \left[1 - \frac{3.555 \times 10^{-3}}{(t^\circ\text{F} + 459.4^\circ)} h\right] \text{ (h = altitude in feet)}$$

Example: for t° = 15°C = 59°F and

p_0 = 760 mm Hg = 29.92 inches Hg:

$\rho_0 = 2.378 \times 10^{-3}$ slug/cf

for t° = 80°F and p_0 = 28.92 inches Hg:

$$\rho = \frac{\rho_0\ (17.32)\ (28.92)}{(80 + 459.4)} = \frac{2.378 \times 10^{-3}\ (17.32)\ (28.92)}{(80 + 459.4)}$$

$$= 2.215 \times 10^{-3}$$

The static pressure p is expressed as a function of the dynamic pressure q: $p = Kq$. The shape of the building and the angle of incidence of the wind influence the value of the coefficient K. There are several studies proposing accurate values of K for different building shapes and proportions and for different parts of the same building. Many of these coefficients have been determined by experimental testing using wind tunnels. A very useful reference in this respect is a 1951 publication from the State University of Iowa entitled "Wind-Tunnel Studies of Pressure Distribution on Elementary Building Forms" (13). Many other values for the coefficient K can be found in the 1961 report of the Task Committee on Wind Forces of the American Society of Civil Engineers (3).

Table 4.—Wind Velocity and Dynamic Pressure

Wind Velocity v (mph)	Dynamic Pressure q (psf)
10	0.26
20	1.0
30	2.3
40	4.1
50	6.4
60	9.2
70	12.6
80	16.4
90	20.7
100	25.6
110	31.
120	37.
130	43.3
140	50.2
150	57.6
160	65.5
170	74.
180	83.
190	92.4
200	102.4
210	113.
220	124.
230	135.5
240	147.
250	160.
260	173.
270	187.
280	201.
290	215.5
300	230.

Venting

The problem of designing adequate venting for balancing the different pressures on the interior and the exterior of a building consists in the determination of the total amount of venting area necessary to allow a certain amount of air to

escape from the building and to re-enter it subsequently. The following data are necessary for the solution of the problem:

a. Maximum value of the pressure gradient

b. Volume of the building under consideration

c. Desired velocity of escaping air

The following example should clarify the procedure: Assume that the maximum pressure gradient is established to be 26 mb/sec, equal to a pressure of 54.3 psf/sec; assume a building whose internal volume is 1000 cubic feet; at a given instant the pressure is assumed to be 2116.224 psf; one second later the pressure is assumed to drop 54.3 psf, according to the established pressure gradient. If we assume that the temperature remains constant, Boyle's law can be applied as follows:

At the first instant the pressure is $p_1 = 2116.224$ psf and the volume of the air in the building is $v_1 = 1000$ cf. At the second instant, one second later, the pressure in the building should drop to $p_2 = 2061.924$ psf, if we want the pressure in the building to be equal to the pressure outside. In order for the pressure to vary the volume should vary so that the new volume at this instant should be v_2. By Boyle's law,

$$p_1 v_1 = p_2 v_2$$

$$v_2 = \frac{p_1 v_1}{p_2}$$

$$v_2 = \frac{2116.224 \times 1000}{2061.924}$$

$$v_2 = 1025 \text{ cubic feet}$$

Because the volume of the building is 1000 cubic feet and cannot expand, the difference between the existing volume in the building and the desired volume represents the volume of air that must escape to balance the pressure: $v = v_2 - v_1 = 250$ cubic feet.

Once the volume of air which must escape has been computed we must decide the velocity of the outflow. Assuming for instance a speed of 30 mph equal to 44 feet/sec, the venting area $A = \frac{v}{V} = \frac{25 \text{ cubic feet}}{44 \text{ feet/sec}} = 0.57$ square foot.

We should try to use low velocity values in order to avoid or to limit damage of household objects. The following table

furnishes the amount of venting area required for the example illustrated above, using different velocity values.

Table 5.—Venting Areas and Outflow Velocity for an Enclosed Volume of 1000 Cubic Feet.

V (mph)	V (feet/sec)	A (square feet)
5	7.33	3.4
10	14.65	1.7
15	22	1.14
20	29.5	0.85
25	36.7	0.68
30	44	0.57
35	51.3	0.49
40	58.7	0.425
45	66	0.38
50	73.3	0.34

Feasibility

The concept of feasibility is too vague to allow only one interpretation. There are several aspects that must be considered individually to arrive at an adequate evaluation of the subject.

The first and probably most important point to establish is whether or not a tornado-proof building is technologically conceivable. The answer can only be found from an evaluation of the factors affecting the design, which are basically two:

1. The nature and magnitude of the forces generated during the storm, and

2. The structure to be subjected to the storm forces, analyzed from the point of view of the peculiarities that differentiate one structure from another.

The Forces. We have seen the differenct values of magnitude of wind velocity, pressure differential, and pressure gradient that have been suggested, estimated, or measured. The several methods used in the determination of these values have been illustrated and the assumptions made in many instances have been presented. At this point the reader can evaluate the degree of dependability of the several data presented and arrive at his own conclusions regarding the values that he will consider most accurate, in proceeding with any design.

The author's opinion will have no more validity than the opinion of any reader, because any conclusion will always be subjective and subject to criticism. Any designer, however,

knows how important it is to have a starting point from which he can make his assumptions, and he realizes that in most cases good judgment is always the basis of any structural solution.

The Structure. The evaluation of buildings with respect to resistance to tornado forces can probably be most meaningful if we divide structures into several categories. In considering the characteristics of the material and the peculiarities of design, the following classification is useful:

1. Reinforced concrete
2. Steel
3. Masonry
4. Wood frame

1. Reinforced Concrete. Buildings in this category are well defined, especially because of the very rigid and detailed ACI code, which in its modern version and in previous editions guarantees the use of constant criteria in the design and in the construction sequences. There is much evidence of the superiority of this kind of construction over other kinds, in withstanding tornado forces. Several authors confirm this fact: Flora writes, "There is reason to believe that the miracle of American architecture, the modern steel-reinforcing building, is proof against serious damage even from a violent tornado and that it provides a safe refuge when one of these storms strikes" (17, p. 76). He adds that although few of these buildings have been in a tornado path as yet, he believes they will certainly survive. Possibly Flora did not have sufficient authority for such statements, considering that his background was in meteorology and not in structural engineering. However, his experience with tornadoes and tornado damage is most dependable. He reports the following events related to reinforced concrete buildings:

In the St. Louis tornado of February 29, 1927, several tall apartment buildings suffered slight damage although nearby conventional buildings were totally demolished.

In Albany, Georgia, on February 10, 1940, the Hotel Gordon, which is a six-story reinforced concrete building, was directly in the path of the tornado. The damage to the building consisted only of broken windows and some cornices blown off. All around there was total destruction.

In reference to the tornado of May 11, 1953, in Waco, Texas, Flora mentions in his book that the Weather Bureau's report

on the damage clearly indicates that reinforced concrete buildings suffered no structural damage. And Flora reports that in a report made by J. A. Wilson, construction engineer, on the damage by the tornado of June 9, 1953, at Worcester, Massachusetts, an interesting claim is made: A monolithic reinforced concrete building with well-supported masonry curtain walls and an average glazed area will resist tornado forces with damage to the roof and windows only.

Information on the destructive forces of tornadoes was compiled in a publication of the U. S. Weather Bureau of November, 1965 (38). In a description of buildings that were torn apart and scattered about it is clearly explained that reinforced concrete buildings are an exception.

What is the peculiarity of this kind of building that makes it so well able to withstand tornado forces? The detailed guidance of the ACI code has been mentioned, but that alone does not explain the superiority of reinforced concrete. The code of the AISC governing steel structures is as detailed as the ACI code, and still there is a certain difference in the performances of reinforced concrete and steel structures.

The most significant factor is probably not the high degree of residual strength due to the coefficient of safety, but the connections, which make up the basic difference between the two concepts of design and construction. By its nature any reinforced concrete structure is a rigid structure, while steel structures in many cases are designed with simple or semirigid connections. Wind action results mostly in horizontal forces, which can be better withstood by rigid frames.

If we can say that a rigid structure such as a reinforced concrete structure can resist tornadoes, then we can probably say that the design of tornado-proof buildings is feasible.

2. Structural Steel. What has already been said for reinforced concrete structures automatically defines the characteristics of structural steel. Rigid connections or equivalent bracings will definitely eliminate any disadvantage of structural steel with respect to reinforced concrete in regard to rigidity, and will therefore increase its ability to resist wind forces.

In the report made by J. A. Wilson and discussed by Flora, which deals with the damage after the Worcester Tornado of June 9, 1953, a comment appears about structural steel buildings. It is claimed that steel frame buildings built and designed according to AISC specifications will resist tornado forces

without damage to the steel frames. Windows, roofs, and metal siding will probably suffer damage.

The Task Committee on Wind Forces of the American Society of Civil Engineers (3) clearly stated that buildings are not designed to resist tornado forces. However, properly designed and properly built structures which have been in the path of a tornado have suffered very little damage. The committee added that damage to well-constructed buildings was attributable to the explosive force of pressure differential rather than to direct wind action.

3. Masonry. This kind of structure considered in the traditional sense is probably the least efficient and most dangerous in connection with horizontal forces occurring during tornadoes. For example in the tornado of June 8, 1966, at Topeka, Kansas, a group of people attending a musical recital in MacVicar Hall at Washburn University escaped death by mistakenly taking shelter in the southeast part of the building. The southwest corner, where they had intended to go, was immediately filled with stones. This incident was reported by Joe R. Eagleman in the **Monthly Weather Review** (16).

Conventional masonry whether of bricks, blocks, or stones has a high compressive strength which depends on the strength of the component elements, including mortar, and a more modest shear strength, while in tension it does not react. The inability of unreinforced masonry to react to tensile forces implies also that only limited bending stresses can be resisted. To be more specific, the only way that bending can occur in masonry is when compression is present too, so that tension is completely eliminated. Horizontal forces can produce very strong bending and shear stresses, against which very little resistance can be expected from masonry structures. Another point against the efficiency of masonry buildings is the lack of continuity between the structural elements such as concrete slabs, steel decks, girders, beams, joists, etc. Usually a steel beam anchored to masonry walls is considered simply supported.

Very critical also is the flying debris that comes from the disintegration of masonry walls. Bricks, blocks, and stones once loosened are usually picked up by the rotating winds and made into destructive missiles.

Modern techniques employing steel reinforcements and high-strength mortars have drastically changed the performance of

masonry structures, eliminating most of the disadvantages mentioned above.

4. Wood Frame. In this category we can group the majority of residences, which constitute the greatest number of existing structures. As we know, the typical building in this category is usually empirically designed on the basis of traditional conventional criteria which take into consideration only vertical loads. The wind loading is usually resisted by the fortuitous stiffness of the structure that stems from architectural rather than structural factors. Partitions and exterior walls parallel to the direction of the wind act as shear walls quite effectively, and they contribute to the stiffness of the structure. It is obvious that if these elements were specifically designed as integral parts of the frame the efficiency and dependability of the structure would be improved to a very great extent. A diaphragm action is provided by the sheathing applied to stud walls. If the number of nails is adequate to allow the wood sheathing to be stressed to the maximum allowable limits, the diaphragms will add a great rigidity to the structure. With the use of walls and partitions as diaphragms the overall architectural design can remain unchanged while the lateral stability can be greatly improved. In addition to the sheathing, or in its place, steel wires can be employed to brace diagonally the existing studs, forming a truss action which will also add rigidity and resistance against horizontal forces. A small steel wire in tension will carry very large loads because of the high stresses that steel can carry in tension. A steel wire of small diameter can be installed in small notches cut in the wood studs without great inconvenience and without appreciably reducing the efficiency of the studs. As previously mentioned some attempts have been made to build tornado-resistant buildings such as the houses on Harrison Street in Kansas City fifty-five years ago reported by S. D. Flora (17). The frames were reinforced using 2″ x 6″ studs instead of conventional 2″ x 4″ and the floor joists were bolted to the studs. The anchorage of the frame to the foundation was also well reinforced. The number of nails used was estimated to be twice the amount commonly used in ordinary construction.

Another important feature of these houses was the venting system, which consisted of two large chimneys that could equilibrate the pressure differential and at the same time act as an additional anchorage of the structure to the foundation.

THE ECONOMIC ASPECT

This aspect of the feasibility analysis should not be considered a governing factor, but it should be taken into consideration before reaching a general conclusion. There are obviously many elements affecting the economical aspect of tornado-resistant design. Basically the problem consists in determining the cost increase due to tornado-resistant requirements and the returning benefits. Among the benefits that could be expected we can mention additional building value or selling price, reduction of damage loss, and reduction of insurance rates. The elements discussed above in this paper must be evaluated, then, in terms of occurrence probability.

The best method of analysis is to study the criteria adopted by insurance companies in figuring insurance premiums. As a comparing element it is interesting to note that in the case of earthquake-proof buildings the additional cost for the additional requirements is apparently low. In a publication by Joseph D. Crumlish and George F. Wirth sponsored by ESSA (14), the authors write, "It is estimated that the added cost of earthquake resistant design increases building costs from 1 to 6 percent. In the California schools, the cost of such design is estimated as close to 1 percent of the building costs." This conclusion is the result of a study mentioned in a footnote, entitled "A Structural-Dynamic Investigation of Fifteen School Buildings Subjected to Simulated Earthquake Motion," written by John Blume, Roland Sharpe, and Eric Elsesser and published by the California Department of Public Works in 1960. The same publication also provides valid information on the economic aspects of earthquake-proof buildings that could be a useful guide in the case of tornado-resistant buildings.

THE PSYCHOLOGICAL ASPECT

Psychological considerations are of great importance but are unfortunately very often completely ignored. The author would like to emphasize this aspect and urge that it be considered a more significant factor in determining the feasibility of tornado-resistant buildings.

Many people living in areas of tornado occurrence experience moments of fear whenever a tornado alert is in effect. The degree of apprehension naturally varies from person to person, and as a subjective factor it cannot be really evaluated. Even if an evaluation of the emotion could be made it would be quite difficult to translate its value in terms of economics.

Probably the best way to establish the economic value of relieving the fear of tornado destruction would be to test the free market and determine how much an average person would pay for the extra features of a tornado-resistant building. This unfortunately requires an investor to risk his capital for an experiment which is very unpredictable.

There are, however, ethical considerations of safety which already underlie many building codes and government ordinances. Earthquake-proof buildings are governed by regulations which could be applied with the same effectiveness to tornado-resistant constructions. From an architect's point of view, the significance of being able to relieve the discomfort of fear by promoting the design of storm-proof buildings is very great. By definition architects usually agree about the intimate relationship between architecture and human reactions, and the concept is an everyday experience for the architectural designer. In some instances, however, it seems that the psychological aspect is not considered with due importance. In the final report of the Task Committee on Wind Forces of the American Society of Civil Engineers, after a comment that structures are not designed to resist tornado forces, and after some discussion of the forces involved in tornadoes, the following statement was made: "No further consideration will be given herein to the subject of tornadoes, because there is no demand for the inclusion of their effects in specifications."

FEASIBILITY OPINIONS

In a bulletin called **News** from the Department of Housing and Urban Development, released October 7, 1966 (41), appears an article entitled "HUD Recommends Ways to Beat Storm Damage." Robert C. Weaver, Secretary of the Department, is quoted as saying, "Much of the loss of life and property caused by hurricanes . . . and by tornadoes can be prevented by relatively simple construction techniques." He then added, "We are making these findings available for builders and homeowners as a public service as well as a protection of the government's interest in housing financed through the FHA or the Veterans Administration."

The bulletin adds that the recommendations made are based on findings of a team of technicians of the FHA headed by F. M. Crompton, an engineer in the FHA Office of Technical Standards. Crompton, who claims that "the forces of a tornado are not irresistible," has said that solid construction will resist

the forces of tornado wind velocities, which he estimates to be approximately between 200 and 250 mph.

In the summary of his article published in the **Bulletin of the American Meteorological Society** in 1958 (31), George W. Reynolds states that, with the exception of dwellings which are in the path of the most severe gradients, the amount of venting required to eliminate destruction is in the order of 12 square feet for a house of 30 x 40 feet of floor area.

A constructive attitude opposed to the fatalism of accepting the destruction caused by tornado is presented in two articles on tornado-resistant buildings: One, by L. V. Teesdale, was published in **Southern Lumberman** in July, 1928 (34), and the other, containing the same information, in **Scientific American** (40). In both articles the opinions of Teesdale, engineer with the U. S. Forest Products Laboratory, are clearly stated. He grouped his recommendations into nine points, of which a major element is the reduction of pressure differential, which he believed could be achieved by proper venting. As a general indication he considered that about 10 to 15 percent of the outside wall area should be a sufficient venting area.

CONCLUSIONS

In evaluating the data on wind velocity we have found some basic differences in order of magnitude among groups of values computed according to different methods. The method of scaling motion pictures seems to be quite accurate and dependable, considering the tangibility of the elements used. The tornado is objectively recorded by the movie camera in its exact visible form. No more dependable and unequivocal documentation has been found. Distances are clearly readable on the pictures, using some element of known length as a unit of measure. The other factor necessary to compute velocities is time, and we know the time elapsed between consecutive frames because it is a characteristic of the camera. There are no assumptions made nor estimated factors included. The velocity derived with this method has a maximum below 200 mph, which is quite low in comparison with other values computed in different ways.

Velocity data computed from the evaluation of structural damage are definitely higher than the values derived from motion pictures. In addition, we must also consider that in the analysis of a damaged structure the force that is assumed to have caused the damage is the **minimum** possible, and there-

fore the derived velocity represents a minimum value, with the implication that the real velocity could be higher. The highest value in this group is 343 mph, computed for the collapse of a transmission tower as reported by Booker. In this case the datum seems to be very dependable because the failure test on the tower had previously been made in the factory with great accuracy. It is also important to note that in this case the wind action was the only possible cause for the collapse, since the tower was a trussed open structure that could not be affected by pressure variation, in contrast to most structures. This velocity estimate, however, stands alone; the next in order is a velocity of 302 mph, computed by Segner for a signboard. About this computation we must also add that Segner himself is doubtful, as he says in his report. The next figure is 285 mph, computed for the overturning of a water tank. We note that in this case, too, the pressure differential does not influence the damage; only the wind action is responsible for it.

The data presented in this study on pressure differential have been divided into three groups: estimated, unofficial, and official values. It is clear that values in the first group, which includes estimates and theoretical values, are far greater than in the others. The unofficial measurements are next in terms of magnitude, and last are the official measurements. We can say that the order of magnitude of these data is inversely proportional to the degree of reliability, assuming that the official measurements are the most reliable.

More important, however, than the pressure differential itself is the pressure gradient, especially if a venting system is adopted. In this case the factors to be evaluated are two: the pressure differential and the time in which the variation of pressure occurs. The time is a function of the translational speed of the tornado, and we have seen that this varies considerably among tornadoes and at different instants for the same storm. It is possible to say that it is unlikely that the maximum pressure differential occurs with the maximum translational speed. In other words, the probable pressure gradient is lower than the maximum value theoretically possible.

Appendix: Pressure Unit Equivalents

(0°C)	1 in Hg	=	33.86 mb
		=	0.4912 psi
		=	70.733 psf
		=	1.133 ft. of water
		=	25.4001 mm Hg
(0°C)	1 mm Hg	=	1.33 mb
		=	0.03937 in Hg
		=	0.0013158 atm (standard)
		=	0.019285 psi
		=	2.77704 psf
(Standard)	1 atm	=	760 mm Hg at 0°C
		=	14.696 psi
		=	29.922 in Hg
		=	1013.253 mb
		=	2116.224 psf
		=	10,333 Kg/m^2
(Metric)	1 atm	=	735.5 mm Hg
		=	14,223 psi
		=	28.958 in Hg
		=	980.665 mb
		=	2048.112 psf
		=	10,000 Kg/m^2
		=	1 Kg/m^2
	1 mb	=	10^3 $dynes/cm^2$
		=	0.752 mm Hg at 0°C
		=	0.0145 psi±
		=	2.088 psf±
		=	0.75 mm Hg at 0°C

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